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Technological change and long-term energy demand

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Abstract

This paper discusses different approaches to incorporating energy technologies and technological development in energy-economic models. Technological progress is an important issue for modelling long-term energy demand and a main contributor to the different energy demand forecasts from different models. The long-term impact on energy demand from using different approaches is compared using Danish models.

The description of technical progress in energy-economy models range from a fully exogenous annual change of energy efficiency to models with endogenous explanations of the innovation process for energy technologies.

Energy demand consequences from one of the modelling approaches are illustrated by examining the energy demand effect of using technological models to describe a number of specific technologies and the diffusion of new technologies. The technological models applied are vintage models for specific energy sectors in Denmark. Vintage models and optimisation models of the energy system include explanation for the diffusion of new technologies and the effect on energy demand. The limitations of the vintage modelling approach in the long term are emphasised.

Vintage models have a long tradition when modelling the energy supply sector. The long lifetime of capital equipment, the limited number of capital units and the known technical coefficients are obvious arguments for a vintage modelling of the energy supply sector. Each capital unit (plant) has relative stable technical coefficients, as changes in energy efficiency, fuel mix etc. require large investments relative to investment costs of a new plant.

Residential electricity demand is also an obvious target for vintage modelling. The stock of individual appliances is very large, but the appliances are homogenous and could be characterised by efficiencies related to vintages. A number of vintage models in this field have been constructed and applied in studies of forecasting residential electricity demand. A vintage model of residential electric appliances in Denmark is applied here.

1. Introduction

Technological progress is an important issue when modelling long-term energy demand. Different assumptions about technological progress are one of the main causes for the very diverging results, which have been obtained using bottom-up and top-down models for analysing the costs of greenhouse gas mitigation. One of the objectives for studies that compare model results has been to create comparable model assumptions regarding technological progress. It is a difficult task to make the assumptions comparable as the modelling approaches differ a lot and in many cases the rate of progress is not explicitly modelled. In other cases the technological progress (efficiency

improvement) is described at a very disaggregated level and never aggregated to a level that is comparable with other models.

In the disaggregated case technological progress can be represented by a specific innovation of some equipment or as the diffusion of a new model of a specific electric appliance. The detailed assumptions about innovation and improvement in the way that some equipment is used could be aggregated and the effect on energy demand compared to an aggregate energy-economic description of the development of energy efficiency. When comparing the effects it is important to distinguish between two different explanations for aggregate energy efficiency developments. The aggregation of specific technological forecasts forms an aggregate assumption about energy efficiency improvement. This **assumption** is one determinant and a description of factors driving technological innovation and diffusion is another determinant.

In energy-economy modelling the description of energy efficiency improvement varies with respect to explaining innovations. The representations range from exogenous and constant rates of efficiency improvement AEEI (autonomous energy efficiency improvement) to endogenised technological development. A constant AEEI can easily be criticised especially if the horizon is short to medium (less than 50 years). The short- or medium-term developments in energy efficiency will depend on a variety of factors as capacity utilisation, vintage effects from new investments, public policy, specific innovation of new technologies and implementation of already known technologies.

In the long run the usefulness of a detailed modelling of technological progress will decline and the description of new inventions and innovations will be the dominant factor in explaining efficiency developments. This is illustrated in this paper by looking at two Danish models. The vintage modelling approach for electric appliances is examined and this approach is compared to a macroeconometric determined demand for heating and electricity. Especially one weakness of the vintage model applied for long term analysis is emphasised. In the vintage model the efficiency of each appliance is well determined but the aggregate of residential electric appliances misses some factors of energy demand. The categories of electric appliances change in time as new electricity consuming appliances are added to the number of existing appliances.

The first part of this paper describes different approaches to incorporating technological change in energy-economy modelling. In the second part a number of examples from Danish models quantify the effect on energy demand projections from different modelling approaches. The importance of different assumptions about technological progress is examined.

2. Autonomous energy efficiency improvement or endogenous technological change

Energy-economy models have very different descriptions of technological change. At the same time technological change is an important element for model properties and the long-term projection results that can be obtained by a model. Model descriptions range from autonomous energy efficiency improvement (AEEI) to endogenous technological progress.

The different approaches to modelling development in energy technology and energy efficiency are based on different approaches to modelling technological progress in general. Links to macroeconomic traditions of neo-classical growth theory and discussions of embodied and un-embodied technological change are obvious. This discussion involves the macroeconomic vintage models. The question of explaining

inventions and innovations in energy and environmental technology are related to the theory of endogenous growth and endogenous technological progress.

Relations to more sector specific and technically based approaches to technology adoption and diffusion are also evident in models of residential energy demand. Epidemic diffusion models have been incorporated in vintage models of appliances in households.

Some of the different approaches to modelling energy technologies and energy efficiency improvement can be categorised by:

- AEEI - exogenous and constant energy efficiency improvement
- AEEI- distinguishing between price-induced and time-induced improvements
- Optimising long-term technology between some aggregate technologies with different efficiencies (energy supply sector)
- Vintage models of capital with energy efficiencies related to vintage (general economy-wide representation)
- Endogenous rate of implementation of known, best available technologies
- Endogenous rate of innovation - R & D related

The autonomous energy efficiency improvement AEEI is an exogenous improvement in energy efficiency in many top-down models. When forecasting, the energy efficiency is projected to rise by an exogenous rate each year, which in different model studies range from an annual efficiency improvement of ½% to 1½%. Apart from this exogenous component of energy demand, the prices of production factors: capital, labour and energy shift the factor input composition. Hereby the energy intensity of production also changes. The AEEI is time dependent but instead of remaining constant the autonomous efficiency change could follow estimated non-linear time trends.

A possible extension of this approach is to link the efficiency improvement to energy prices, but it will be hard to establish an empirical distinguishing between price-induced shifts in factor inputs and price-induced improvement of efficiency.

An AEEI representation of efficiency improvement in specifications of energy demand for heating in households could, for example, be

$$E_j = e(p_i, p_j, aeei, C) \quad (1)$$

E_j Energy demand delivered by different heating technologies

p_j Price of different heating technology: electricity, district heating, natural gas, etc.

p_i Price of other consumer goods or services

$aeei$ Autonomous energy efficiency improvement (indexed)

C Total private consumption

The AEEI representation in households thus accounts for efficiency improvements induced by improved insulation of existing houses, efficiency improvements in specific heating technologies, standards for new dwellings and the introduction of new heating technologies not represented in the modelling specification.

While technological development in energy use in economic modelling is often considered in terms of a constant rate of change in energy efficiency, the technical view would emphasise the specific technologies and estimates of future rates of introduction of new technologies. The technical view includes limits on the increase in energy

efficiency. For existing technologies these limits seem plausible, as fuel efficiencies would hardly increase above 100%. In contrast the technological change from an economic view is an aggregate of changes in production technology for existing products and a change in the output mix with a stream of new products partly produced with existing and partly with new capital equipment. The economic view does not have any assumption of limits for energy efficiency or decreasing rates of energy efficiency improvement in time. Only when production of a single output or a very specialised sector is examined will production technologies be modelled in detail, and thus the properties from technological models will arise.

Energy-economy models with optimisation of the choice between specific energy technologies dependent on total discounted profits and based on rational expectations include exogenous assumptions regarding the availability of the specific technology in time. The resulting average energy efficiency is then endogenous in the way that changes in prices by environmental taxation have an impact on the optimal choice of the technology. Models of this kind are developed mainly for optimising energy supply systems.

Vintage effects through different energy efficiency for different vintages of capital could be important for year to year changes in energy efficiency. Vintage models can describe diffusion of new technologies or improved technologies. This kind of vintage model of capital has been applied to fields of energy relevance. Both technical vintage models of durable consumer goods (appliances) and vintage models of energy supply exist. More macroeconomic based model approaches of capital vintages for producing sectors in general and their energy efficiency have also been proposed.

Hogan and Jorgenson (1991) analyse another aspect of technological change. The effect of higher energy prices through fuel taxes with the objective to reduce CO₂ emissions could have impacts not only on the rate of change in energy technologies but also on the general productivity. They find that technology change has been negatively related to energy prices. If energy prices increase the rate of productivity growth will decline.

Long-term energy demand and environmental issues related to this will depend very much on the possible invention of new technologies. These could be new energy technologies, but they could also be production technologies, inventions in transportation etc. Thus energy efficiency will depend on technological developments that have nothing to do with an aim of improving energy efficiency. This dependence means that no energy or environmental policy option exists for influencing this part of energy efficiency development.

Innovation with specific relevance for energy technologies is a more relevant area to model if the aim is to analyse possible policy instruments that influence energy efficiency. Carraro and Galeotti (1997) describe an endogenous modelling of innovation in energy technologies. The innovation is related to R&D, which again is endogenously determined by prices, output and policy variables as environmental taxes and R&D subsidies. Their model (WARM) is an econometric general equilibrium model of the EU. The endogenous technological progress has been analysed in many theoretical models but the WARM model has an advantage in that the technology representation is empirically founded. R&D activities are assumed to be connected with positive externalities and this causes firms to under-invest in R&D. They argue that a policy mix of taxes to increase adoption of energy saving technologies along with subsidies to environmentally friendly R&D should be considered. Through such a policy it seems possible for the economy to follow a growth path without environmental harm.

Ulph (1997) surveys a number of recent studies based on a game theoretic approach to firms decision to invest in R&D. He considers two different ways of modelling possible R&D paths. Non-tournament models with more than one R&D path leading to innovations that are capable of producing the same final product and tournament models with just one possible invention capable of producing a specific final product. All firms in the second case compete to make this innovation and have it patented. Ulph finds that environmental policy in the case of taxes will stimulate R&D in non-tournament models, whereas the effect in tournament models will depend on competition in product markets.

Jones (1994) examines the question of incorporating a technological trend in econometric studies of aggregate energy demand. There are several technical problems connected to including technical progress. The main problem is the difficulty of distinguishing between technical progress and long-term price effects. Jones finds econometric evidence that technical progress is around 1½ % annually with plausible long-term price elasticities at the same time. The long run income effects are not significant.

Ausubel (1995) points to the long-term trends for improving efficiency of different kinds of equipment. Why should an observed trend of decreasing carbon intensity in electricity production be reversed in the future? His remark raises the question of a possible difference between the improvement of efficiency for a specific technology and the improvement in aggregated efficiency caused by the innovation and introduction of new technologies.

In a model for Austria Glueck and Schleicher (1995) examine a possible effect on technological progress of CO₂ reduction policies. This is an example of policies that can accelerate the diffusion of more energy efficient technologies. But the study does not address the issue of technological progress in the form of the innovation and improvement of energy technologies.

Clarke and Edmonds (1993) in a model of energy technology choices and product price formation point to an aspect of new technologies that could be important for the diffusion of new technologies. Production costs for every technology is related not only to the cost characteristics of the technology itself but also to other factors as: geographical location (transport), skills of local workforce etc. New and on average more costly production technologies will enter the market. But the impact of the new technology on output prices will not be to increase prices because the new technology will be employed only in the instance where production costs of the new technology are below the market price. This observation might explain why some technologies that based on average production costs seem un-competitive capture market shares anyhow. It could be added that new technologies might include more uncertainty on costs than existing technologies. The producer who successfully introduces a new technology will have an advantage relative to the competitors.

3. Long term energy demand

The different approaches to modelling energy efficiency developments affects the long-term energy demand that the models project.

Vintage models do describe the aggregated efficiency developments including the restrictions from the efficiency of past capital vintages. In the long run the vintage effect on average efficiency becomes less important and the annual efficiency improvement will be more stable. In the case of electric appliances the vintage models have some

disadvantages to other approaches which will be evident in the case of long run energy demand. This is examined below, where a macroeconomic model of Denmark ADAM and a Danish vintage model for electric appliances are compared with respect to long-term energy demand projections. It is examined whether it is different assumptions about technological progress, that leads to different energy demand projections. The vintage model of electric appliances and the model of residential heating demand are documented in Jacobsen et al. (1996).

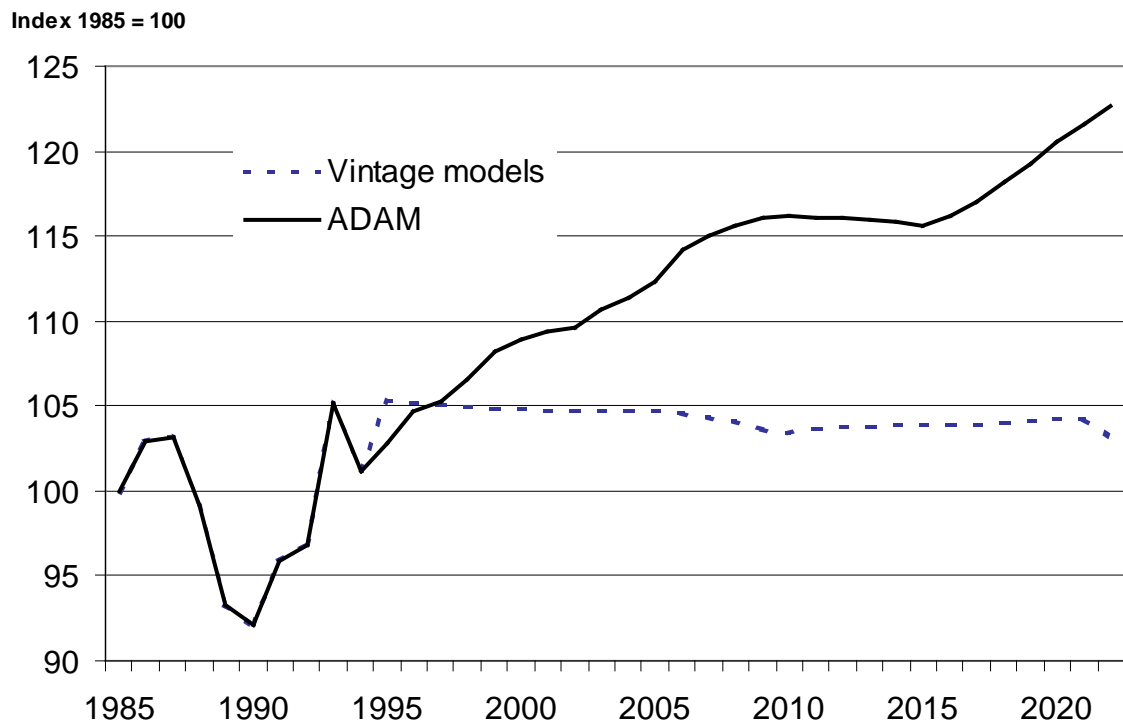


Figure 1 Residential demand for electricity and heating

The two model projections of residential electricity and heating demand differ very much. The driving factors in the vintage models housing area, population, and consumption of durable goods are the variables determined in ADAM, which ensure that the macro assumptions are consistent between the two models. The main reason for the difference could be suspected to be different assumptions about the improvement of efficiency. ADAM does not include any explicit assumptions of efficiency, but the income elasticity of this component of private consumption is low .94 compared to 1.75 for durable goods. This is reflected by comparing the average growth rate 1985-2020 for electricity and heating 0.53% with the average growth of total private consumption 2.29%. Another explanation for the slower growth of this component is a real increase in the consumer price of electricity and heating in combination with the long-term price elasticity in ADAM, which is -0.89 .

Electricity demand for appliances is modelled with vintages of appliances where each new vintage is improved with respect to electricity consumption. The efficiency development for the electric appliances is specific for the individual appliance, but a weighed average of the 16 categories of appliances constituting residential electricity demand in the vintage model can be constructed. With weights of projected energy demand by category for 2020 the average annual efficiency improvement 1985-2020 is 0.91%. This is not an unreasonable high efficiency improvement, and thus not a main

explanation for the difference in projected energy demand. Another explanation and a major point of criticism of vintage models for appliances is the category named “other appliances”. This category is relatively small at the outset of the projection period around 1995, but how does this category evolve in the projection? In our case no link to economic activity exists for the category and the category remains small. Contrary to this it would be expected that in the long-term the growing economy would increase the number of appliance categories with significant electricity consumption including some technologies not even existing today. This is a more important difference between the modelling approaches than the actually applied rate of technological progress and the importance increases as the horizon of analysis is expanded.

To compare with the macroeconomic determination of residential electricity and heating demand the efficiency in heating must be examined. Residential heating is described in a model including different local heating technologies applied at the residential level. The local effectiveness and the share of these technologies are projected. Residential demand for heating is determined by combining the effectiveness with the housing area and parameters for climate and desired room temperature.

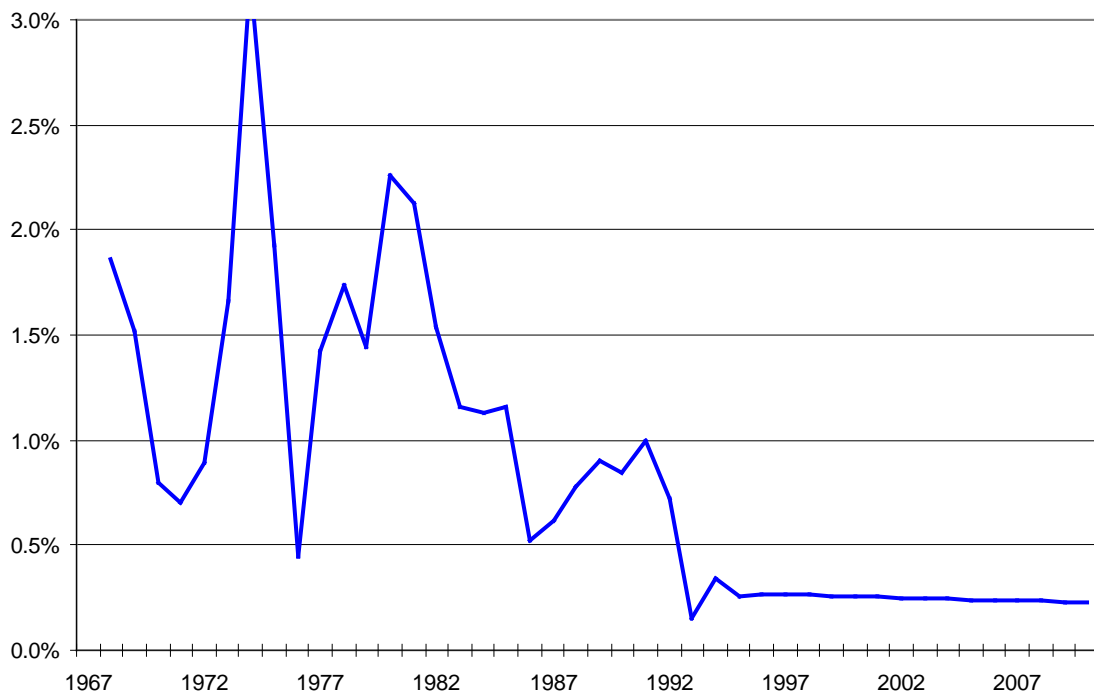


Figure 2 Average annual increase in local efficiency for six heating technologies

The figure shows historically large variations in the annual improvement in efficiency. This is seen even though the figure shows two-year moving averages of efficiency increases with efficiency weighted by the share of the heating technologies. In the projection the efficiency follows a steady improvement but with much lower annual increases than historically. There are many arguments for slower efficiency improvement, among which the composition argument is most important. The change from local oil based heating technologies towards district heating accounting for a share of around 50% of households heating technology today will not proceed at the same speed and even for the local efficiency the oil burners will probably only be marginally more efficient than the 70% that is the case today. The projection of an efficiency increase

of around .25% annually is very moderate and thus the technology assumption in the model of residential heating is not the reason for the divergence in energy demand projections between the two models.

Another issue for comparing energy demand projections from models based on different approaches and just as important is the difference of policy effects among the approaches. In some models long term energy demand can only be affected by exogenous price changes or taxes. In other models a range of policy instruments can influence the efficiency developments. In the models mentioned above the policy instruments are very different. In ADAM the policy instrument is to increase energy taxes for households. In the vintage model taxes also has an impact on the intensity of use for some of the appliances, but the effect is limited. The vintage model due to its detail includes a number of policy instruments.

- Electricity tax
- Standards for new vintages for each of the 16 appliance categories
- Indirectly through taxes on the purchase of durable goods

The effect of the electricity tax is rather moderate compared to the effect in ADAM and the effect only works through the intensity of use. There is no effect on the volume of new purchases and no effect on the choice between brands of appliances with different efficiency. Thus there is no effect on the composition of vintages with different efficiency and the effect on aggregate efficiency is small as only some of the appliance categories have price elasticities for intensity of use and the elasticities are quite small around -0.1.

Standards are a direct regulation on the maximum electricity consumption for a vintage of a specific appliance. Through the replacement of old vintages and the modelled increase in coverage standards affect the average efficiency improvement and the long-term electricity demand.

The last policy variable works through taxing the purchase of durable goods. The ADAM consumption group has a very high income-elasticity and a long-term price-elasticity of -1.52. The consumption group through a link to the vintage model affects the rate at which coverage increases by using an estimated relation between the consumption of durable goods and the purchase of each category of appliance. The volume of vintages of different appliances is affected, but the level of saturation (the maximum coverage percentage of households in possession of a given appliance) is not affected. Thus the impact on electricity demand is of a temporary nature and works through the stock of appliances and the average efficiency of the stock.

In the vintage model policy options influences energy demand both through a change in intensity of use, the stock of appliances and the average efficiency of the stock. Among the policy options standards is the most powerful one and this policy works through the diffusion rate for the least electricity consuming brands of an appliance.

4. Conclusions

Energy demand modelling include a variety of approaches to describe technological progress. Technological progress is also a key issue for modelling long-term energy demand. Macroeconomic energy-economy models have a very aggregated and generalised description of the change in energy technologies. It is possible to endogenise technological progress at the aggregated level, but it is very difficult to establish empirical results to verify the endogenisation. Another approach is to emphasise a

disaggregated description of existing technologies and the technologies, which are at a promising development stage. This excludes the description of fundamental innovation, which is a highly relevant question when attempting macroeconomic modelling to endogenise technical progress, but it improves the description of existing technologies and makes it easier to evaluate the assumed efficiency improvements at this level.

Long term energy demand in Danish models can be compared with respect to the significance of the description and assumptions about technological progress (energy efficiency). Vintage models of electric appliances shows that the energy demand forecast differ from a forecast with a macroeconometric model ADAM. The ADAM demand relation does not explicitly include efficiency, but involves an income-elasticity less than unity. The vintage model includes efficiency assumptions for all new vintages for 16 categories of electric appliances. It is not the disaggregated assumptions of efficiency, that is the main reason for the difference in energy demand forecast. If the technological assumptions are aggregated and weighted by electricity consumption the average projected efficiency improvement is rather moderate with .9% annually. Instead it is one property of this vintage model that in the long run tend to moderate the growth of electricity demand. No explanation for new appliances and the economic driving forces for this category of appliances is included. The conclusion is that a vintage model of electric appliances even if it includes linkages to economic activity and income should not be applied in the long run.

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